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Comparisons of wave kinematics models for an offshore wind turbine mounted on a jacket substructure

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Abstract

The purpose of this study is to investigate the dynamic influence of wave loads for wind turbines placed at intermediate water depths (40-60m) using a jacket substructure. We analyze whether nonlinear wave loading may lead to "ringing", which is a transient excitation of structural modes with much larger amplitudes than seen for linear wave kinematic models. Full interaction between dynamics of the wind turbine and the substructure is included in the study performed for a standstill situation using the fully flexible aeroelastic code HAWC2. Wave loads are modeled using classic methods like Airy and stream function theory, but also a new and more advanced fully nonlinear irregular model has been applied. This nonlinear wave model solves the 3D Laplace equation for the velocity potential with nonlinear boundary conditions at the free surface and an impermeability condition on the sea bed on a variable depth, representing state-of-the-art within nonlinear irrotational wave modeling. The results show a significant increase in dynamic load contribution by the nonlinear waves.

1 Introduction

Within the offshore wind industry there is a general trend towards constantly increasing turbine sizes and siting conditions at water depth above 30m, which has a direct consequence for the design of the applied substructure. Until now, mainly gravity based concrete foundations and monopile have been utilized. However, for increasing water depth and turbine sizes other concepts seem competitive. Especially hydrodynamic transparent designs like the jacket construction attain increased attention since they appear to be cost effective for intermediate water depths. For very deep water, floating designs seem to be the only feasible design.

In general the wave loads are more simple to simulate for deeper waters where small waves are described very well with the linear Airy method [1]. This simple wave model has the benefits of being easily extended to irregular wave trains with and without wave spreading. An improvement of the kinematics near the free surface is obtained by mapping the wave kinematics from the sea bed to the still water level onto the full water column stretching from from the sea bed to the instant wave surface height. This is referred to as the Wheeler stretching [2]. Steep waves (though not breaking) can be represented using stream function theory [3] and [4], which provides a fully nonlinear solution for regular waves on constant depth. These methods are especially applied for investigation of extreme load in storm situation. An offshore wind turbine however differs from most other offshore structures by

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a high degree of flexibility, mainly caused by the flexible tower and heavy top mass in the nacelle and is designed by an equal weight of fatigue and extreme load. It is therefore not obvious that the current design practice using linear wave methods for fatigue load simulation and stream function loads for extreme loads is adequate. In order to investigate the effect of the nonlinear wave loads a recently developed method has been utilized. This method is based on a solution of the 3D Laplace equation for the velocity potential with nonlinear boundary conditions at the free surface and an impermeability condition on a variable depth as described in [5]. This wave model is fully accurate for irregular waves on flat or sloping sea bottom provided that the waves do not break. The solution is based on a finite difference solution of a wave field in time and space. In the inlet of the domain, linear wave conditions are applied. These waves propagates through the domain over a sloping bottom thereby developing to be steeper and more nonlinear towards the domain outlet. Recently, a study of the wave loads on a monopile structure at a depth of 30m has been presented [6], where the influence of wave nonlinearity was shown to be significant for the largest waves. The main limitation of the wave model is the in-ability to accurately describe breaking waves. In the present stude an ad-hoc filter that removes local energy where the waves would physically break was applied dynamically in the computations. While this prevents numerical break-down caused by non-physical large-amplitude waves, it should be noted a more physically breaking sub-model is subject to current research. In the present study, the filter was mainly effective for the wave climate of the largest significant wave height. Time series of the elevation, velocity and acceleration is extracted at a water depth of 50m and inserted to the structure using simple lookup and linear interpolation methods.

An example of the difference in the applied wave load models can be seen in Figure 1. In this figure it is seen that the linear wave is irregular and that the through and crest is of same magnitude. The stream function wave cause a higher magnitude of the crest compared to the through, but is regular. In this paper the wave height of the stream function wave is set equal to the significant wave height of the irregular waves and the time period identical to the peak period. Other approaches for the wave height could have been chosen, for example to try to match the properties of the largest wave observed with linear tools. This, however is left for future study and it should be kept in mind that the stream function wave is simply chosen to obtain a first measure of the associated loads. The nonlinear wave has a larger crest height than through depth and is highly irregular. It is not possible in this figure to compare the crest and through levels between the different models since it is based on a very short time window. This is instead shown in Figure 4 for the selected wave cases.

The wave kinematics is converted to structural loads using the Morison equation [7] in a form where relative motions are considered separately from the Froude-Krylov force contribution. This is considered adequate for the jacket construction since the individual beam members are slender compared to the wave lengths applied. Slap and slam load contributions are not included. Contributions from slap or slam are only expected to increase the load contribution from the largest waves, hence increase the load impact from the nonlinear waves.

2 The "ringing" phenomena

"Ringing" is a phenomenon occuring when waves excite a dynamic flexible structure as illustrated in Figure 2. Typically this occurs when single large waves pass the structure causing single large impulse loads that excite both low and high frequent structural vibrations. A related term is "springing", which is a general increase in dynamic response caused by resonant excitation from the general wave energy at the structural frequencies. Both terms are sensitive to the wave load model applied. Using nonlinear wave theory, the individual wave heights are higher than for linear waves increasing the potential for "ringing", but nonlinear waves also include more high frequent components, which is likely to increase the general "springing" affected load level.

3 Investigated problem

In order to investigate the influence of nonlinear wave loads on a relevant and replicable design, the fictious 5MW wind turbine [8] used in the benchmark projects IEA Annex 23 OC3 and IEA Annex 30 OC4 has been used for the modeling of the wind turbine. The jacket design is also from IEA Annex 30 OC4 [9], which is based on a design previously used in the European research project UPWIND. The turbine and jacket are sketched in Figure 3 (left) and Figure 4 (right). The jacket design consist of 4 corner piles interconnected by 3 sets of braces in X-configuration. The piles are flooded, whereas the braces are closed and thereby contributes significantly

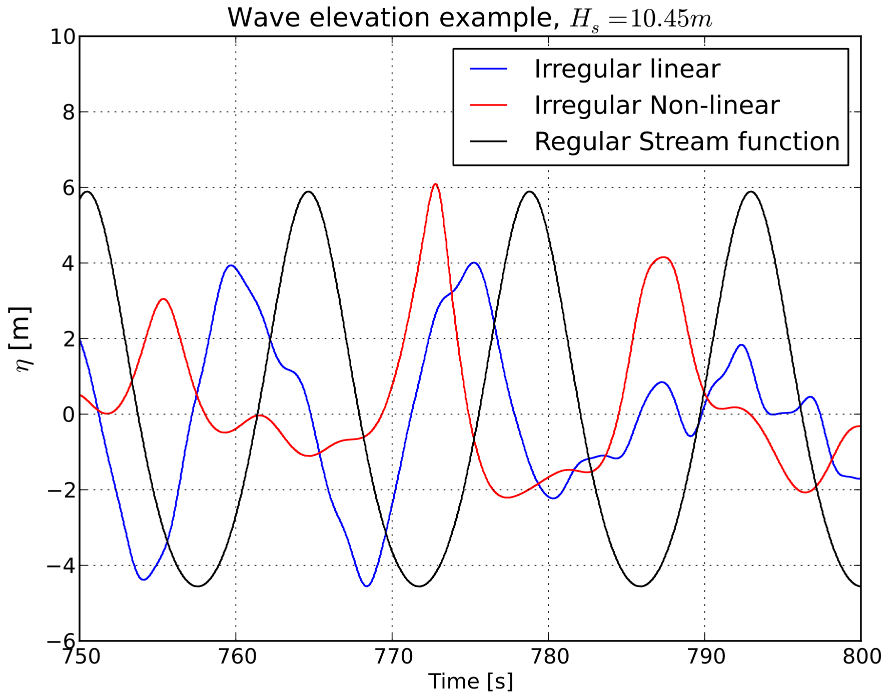

Figure 1: An example of the wave-elevation of the different wave types is shown. The stream function wave has a more narrow wave top compared to the linear wave, but is constant amplitude. The fully nonlinear wave also has this feature, but is further characterised by being fully irregular containing same energy spectrum as the linear waves. The amplitudes of the shown waves are not representative since this is only an extraction of a small random time window. For information about the significant wave height, see Figure 3.

with buoyancy. The top of the jacket includes a transition piece to the tower bottom 20m above still water level. This consist of a large volume of reinforced concrete with a total mass of 660t. This configuration seem to be a heavier construction than several other jacket designs, however it was chosen for the IEA Annex 30 project and therefore also used in this study. The fictitious turbine has a rotor diameter of 126m and a hub height of 90m. The top weight consisting of nacelle and rotor is 350t. The still water level is 50m. The investigated situation is for the turbine at standstill, where the blades are pitched 90deg and the waves are in a direction directly towards the wind turbine direction. Since the blades are pitched, the aerodynamic contribution is considered very low and aerodynamic loads on the tower are also neglected. This load condition is considered highly relevant for offshore turbines and is known to be problematic for monopile configurations since the total level of structural, aerodynamic and hydrodynamic damping generally is very low at stand still. The significant wave height and peak period and depth are shown in Table 1 and in Figure 3, where the model validity of classical wave theories and wave breaking criteria are also shown. The wave data was selected to be representative for waves in the North sea and are all outside the valid range for linear wave theory.

Since the focus in this paper is both the influence of extreme loads and fatigue loads every stochastic simulation case consist of three half-hour simulations, each with different seed input. The nonlinear wave solution is however computed for several hours, so instead of choosing different seeds, different half-hour time windows were used. The max,min,mean values as well as equivalent fatigue loads were calculated as the average value of the three simulations to decrease the statistical uncertainty.

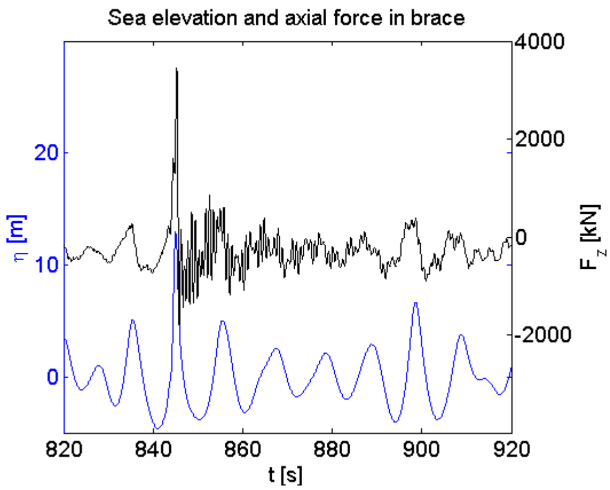

Figure 2: "Ringing" may occur when a single large waves pass the construction causing a large impulse load.

Table 1: Wave data for the 5 selected wave cases.

Case no.	H_s	T_p	kh
1	2.27	6.84	5.2
2	3.11	7.92	3.5
3	5.11	10.46	2.2
4	7.15	12.32	1.6
5	9.46	14.16	1.3

4 Results

A set of sensors has been compared for the different load cases. First of all the wave elevation was compared in Figure 4 (left). In this figure it is seen that all the stochastic models give identical through levels, whereas the nonlinear irregular wave model shows significantly higher crest level. The stream function wave also results in an asymmetric variation as the nonlinear, but the absolute variation is significantly smaller since the wave is regular.

In Figure 5 the results of the different waves impact on the structural loads are seen for selected sensors. In the left column of subfigures is shown the average maximum,mean and minimum load for the simulations as function of significant wave height. To the right is shown the 1Hz equivalent fatigue loads for a wöhler exponent of m=4, corresponding to normal steel structures. From top is seen the longitudinal tower bottom bending moment just above the transition piece, the axial force in the front right leg just below the top X-brace connection in the K-joint, the axial force in the lower X-brace on the front side and the axial force in the upper part of the right pile on the back side. The locations of the sensors is also shown in Figure 4 (right).

A small increase in loads is seen for the linear waves when Wheeler extrapolation is included, as compared to the linear case where only the kinematics up to the still water level is applied. The load increase from the nonlinear waves is however much more pronounced and seen to increase the load level for all the simulated wave cases. For the small significant wave height the increase in load level is likely to be caused by "springing" where "ringing" is seen for the large significant wave heights. The increased load effect is seen for all sensors on the structure but is especially pronounced for the tower bottom bending load and the leg load in the upper part of the substructure. For the cases with small significant wave heights, the increased high frequency content in the nonlinear waves seem to cause a general small increase in loads, which fits very well with the springing affected loads. The mechanism is however different for the large significant waves where ringing occur. Here the single large waves in the irregular wave train is of a magnitude large enough to excite the structure and cause large transients after the wave passing. The excitation is mainly on the first structural frequency at 0.32Hz and due to the low amount of damping, the vibration levels become large.

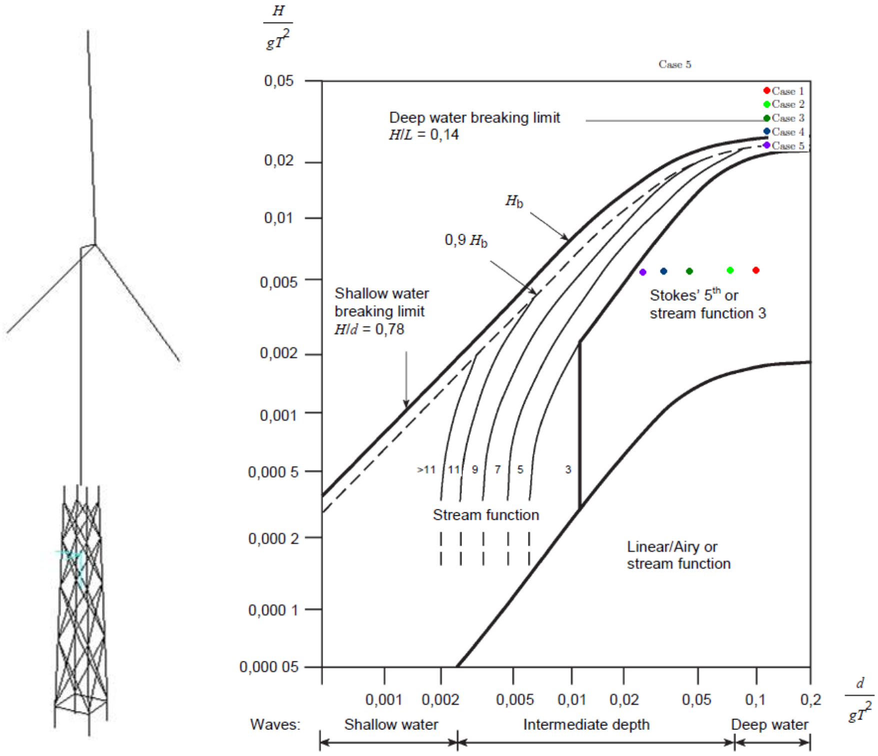

Figure 3: The jacket is shown to the left. To the right is shown the properties of the five selected wave sizes.

5 Discussion

As far as the authors are aware, this is the first time a set of simulations for a flexible offshore turbine mounted on a jacket substructure has been investigated for dynamic affected loads using irregular highly nonlinear wave kinematics. The results clearly show a significant effect, which can be of crucial importance to the industry. Since the results are the first of their kind, the results also need to be treated with care until other work, this may be simulations or experiments, show similar behaviour. The HAWC2 model of the turbine and jacket has been used in several benchmark projects on this specific turbine and substructure (including other types of substructures) and has shown to generate results reproducible by a large quantity of similar advanced codes in the IEA Annex 23 and IEA Annex 30 projects [10],[11],[12]. Regarding wind turbine response, it has been compared in detail with several full scale measurements and is in general considered to be state-of-the-art within aeroelastic wind turbine simulations. The nonlinear wave model has also been compared to experiments and shown to be very accurate as long as the waves are below the breaking criteria. The usage of Morison's equation in the transfer of wave kinematics to structural loads is also expected to give good results for this type of substructure. One limitation could be the lack of slap and slam load consideration, but this is only expected to increase the dynamic load effects for especially the large nonlinear waves. Some of the uncertain parameters related to the study is related to the amount of damping present in a structure of this type. In the HAWC2 model a damping expressed as a logarithmic decrement of 2% on the first natural frequency has been applied. In reality it is uncertain how much damping is provided by the soil, aerodynamics and from wave radiation, however these contributions is considered to be of low magnitude. It is also not clear what the effect of the very large mass of the transition piece is. In most other industrial concepts a more light weight transition piece is used, which could change the structural dynamics.

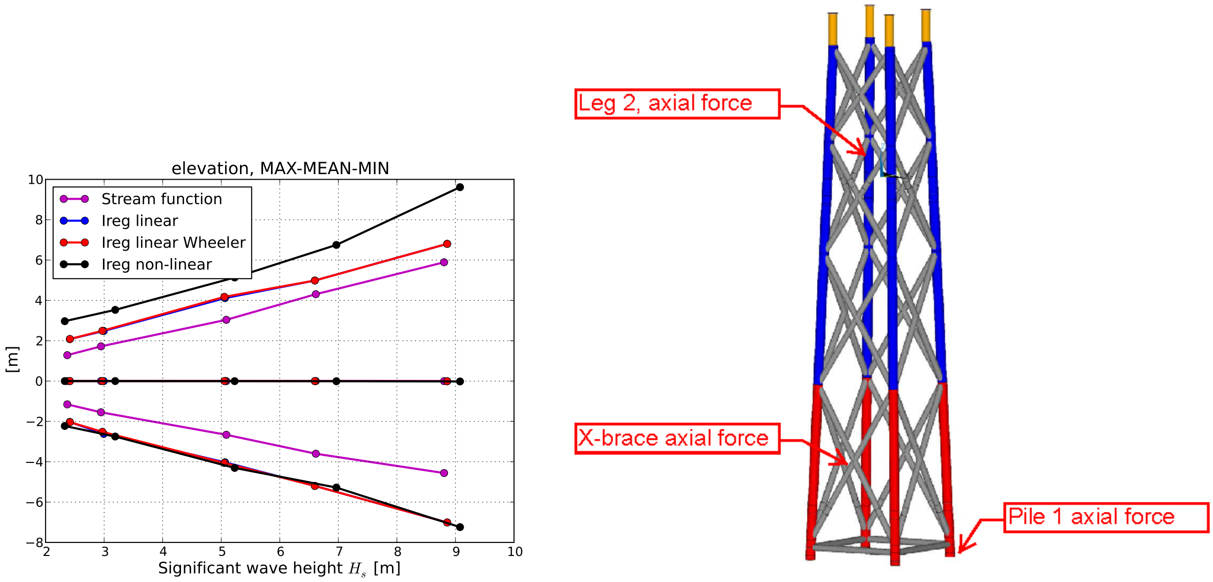

Figure 4: Left: An overview of the max and minimum wave elevation levels for the selected significant wave heights. Of obvious reasons the irregular wave have higher variation in the wave elevation than for a regular stream function wave. The nonlinear waves have same level of wave through whereas a significant increased wave crest level is seen. Right: Illustration of the selected load sensors, courtesy [9]. Leg 2 is front right towards the incoming waves, where pile 1 is on the back side.

6 Conclusion

Nonlinear irregular wave loads have been applied to a flexible structural model of a 5MW offshore wind turbine mounted on a jacket substructure at 50m water and compared to classic linear wave theory and stream function waves. The results are two-fold. First conclusion is that "ringing" is very likely to occur for jacket type foundation on intermediate water depth (40-60m) when waves are close to breaking. This will especially increase the dynamic loads on the lower part of the tower, but transients are also seen in the braces, legs and piles of the substructure. Secondly, nonlinear wave models are important for the prediction of the general load level and cause a higher load level than predicted using linear wave models. Since the study as far as the authors are aware is the first of its kind, the obtained results should mainly be considered indicative until verified by other simulations, experiments or full scale observations. However, the applied methods is considered state-of-the-art and it is therefore probable that these dynamic load can and will occur.

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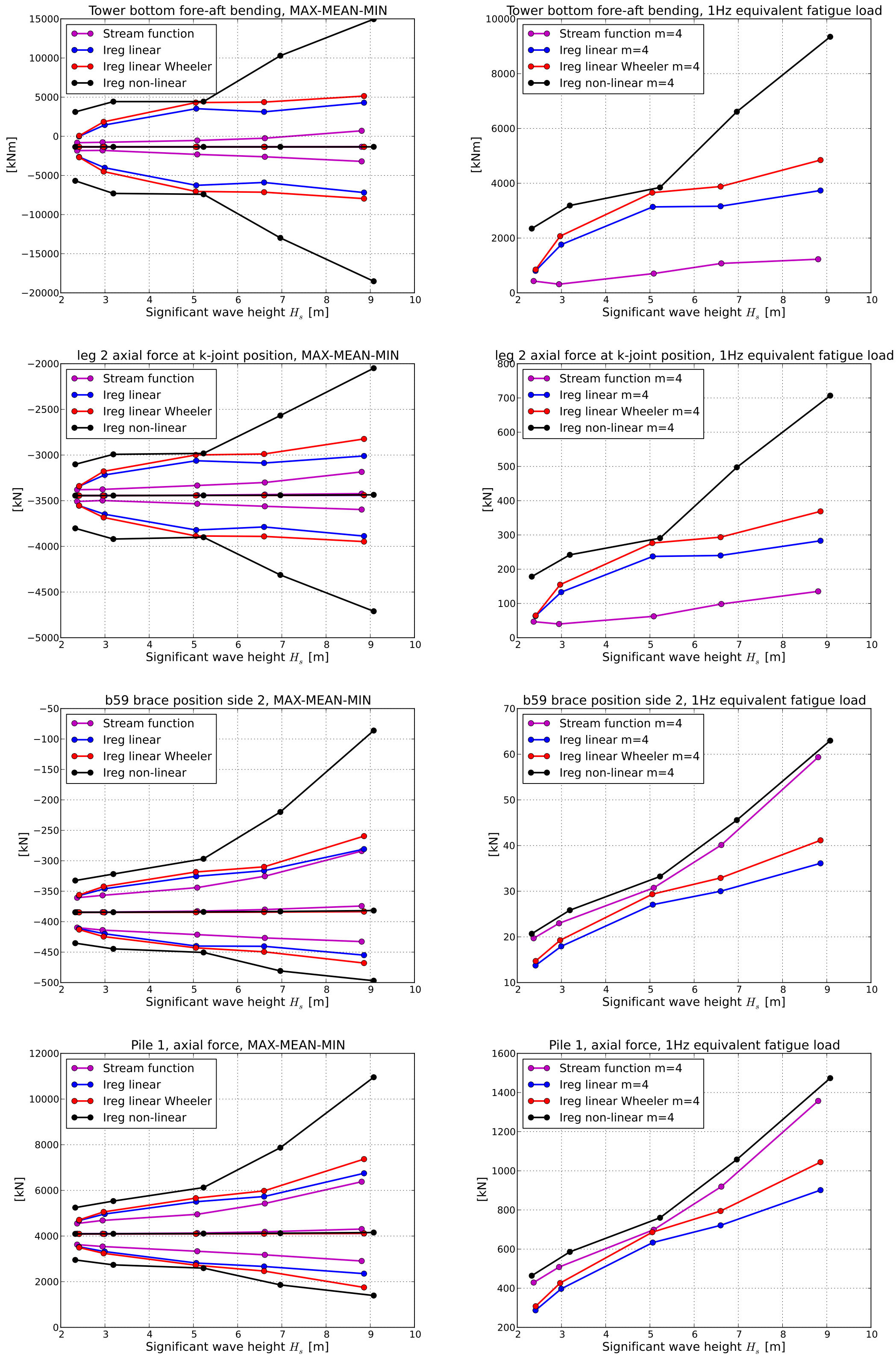

Figure 5: The simulated loads shown for tower bottom fore-after bending, axial forces in leg 2 below the K-joint, axial force in the lower X-brace and the axial force in pile 1. A clear increase in loads due to the full nonlinear loads is seen. To the left the max-mean-min loads are shown. To the right the 1Hz equivalent fatigue loads are shown.

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